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Baseline

The size, mass, and composition of plastic debris in the western North Atlantic Ocean

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ABSTRACT

This study reports the first inventory of physical properties of individual plastic debris in the North Atlantic. We analyzed 748 samples for size, mass, and material composition collected from surface net tows on 11 expeditions from Cape Cod, Massachusetts to the Caribbean Sea between 1991 and 2007. Particles were mostly fragments less than 10 mm in size with nearly all lighter than 0.05 g. Material densities ranged from 0.808 to 1.24 g ml^{-1}, with about half between 0.97 and 1.04 g ml^{-1}, a range not typically found in virgin plastics. Elemental analysis suggests that samples in this density range are consistent with polypropylene and polyethylene whose densities have increased, likely due to biofouling. Pelagic densities varied considerably from that of beach plastic debris, suggesting that plastic particles are modified during their residence at sea. These analyses provide clues in understanding particle fate and potential debris sources, and address ecological implications of pelagic plastic debris.

Plastic debris has become increasingly recognized as a global ocean-wide problem due to its ubiquity and recalcitrance, allowing particles to persist for estimated years to millennia (Andrady, 2003; Barnes et al., 2009). Due to its buoyancy, plastic debris is widely dispersed in the open ocean; however, physical forcing leads to accumulation in convergent zones resulting in regions of high concentrations near the centers of subtropical ocean gyres (Pichel et al., 2007; IPRC, 2008; Law et al., 2010). Plastic consistently composes 60–80% of all marine debris (Derraik, 2002); the major sources to the ocean are runoff from land and the intentional dumping or loss of fishing gear and other plastic objects from ships (Pruter, 1987).

Plastic debris can have deleterious effects on marine organisms. Plastics release phthalates by exposure to sunlight and direct leaching, (Giam et al., 1978; Teuten et al., 2009), which may disrupt the endocrine system of mammals (Li et al., 2004). The particles themselves can cause harm or death to seabirds and large marine fauna from ingestion or entanglement (Azzarello and Van Vleet, 1987; Laist, 1987; Derraik, 2002), and may affect lower trophic levels as well (Laist, 1987; Thompson et al., 2004; Browne et al., 2008). They provide substrate for the transport of sessile organisms (Minchin, 1996; Barnes, 2002; Gregory, 2009) and are potent carriers of persistent organic pollutants due to their hydrophobic, lipophilic nature (Mato et al., 2001; Teuten et al., 2007; Colabuono et al., 2010).

While previous efforts have shown that plastic debris is prevalent along the coastline (Ribic et al., 2010) and immediately offshore of the eastern United States (Carpenter et al., 1972; Colton et al., 1974; Van Dolah et al., 1980), little is known about the distribution of plastic in the North Atlantic Ocean, especially east of the Gulf Stream. Moreover, there is even less information about physical properties of the debris such as individual size, shape, density, and elemental composition. The scarcity of plastic debris data on an individual-particle basis limits long-term studies on any trends in plastic debris in the North Atlantic and elsewhere. Most studies to date have limited the discourse of marine plastic distribution to a geographic context, and no spatial trends have been catalogued concerning the physical and chemical makeup of plastic particles in the neuston (air–surface interface) layer. In this manuscript we provide spatial and physical data that establish a baseline for the *statistical* distribution of plastic properties.

We analyzed the physical properties of 748 individual particles, a subset of more than 18,000 archived plastic samples collected in the western North Atlantic Ocean by Sea Education Association (SEA, Woods Hole, MA, USA) over the past 24 years. Plastic particles analyzed in this study were collected aboard the RV *Westward* and SSV *Corwith Cramer* on 11 cruises during the months of October and November between 1991–1995 and 2004–2007 (Fig. 1). Collected samples spanned latitudes 11–44°N and longitudes 55–71°W. Our analyzed samples represent a subset of individual par-

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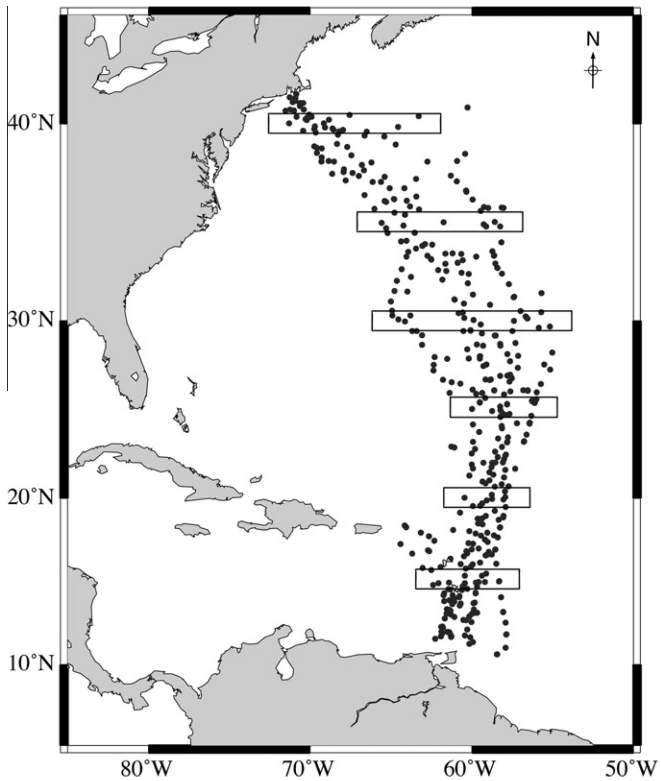

Fig. 1. Neuston tow locations on 11 cruises between 1991–1995 and 2004–2007. Analyzed plastic samples were collected from tows at every 5th parallel, within 1° latitudinal bins, indicated by rectangles.

ticles selected from tows at every 5th parallel, enclosed in bins spanning 0.5° north and south of that latitude (1° total). This sampling scheme allowed us to investigate geographic trends in plastic particles at a realistic scale while maintaining proportionate representation within the region of high plastic concentration in the North Atlantic. Data are presented in these latitudinal bins (15°N, 20°N, 25°N, 30°N, 35°N, and 40°N, all ±0.5°) without respect to longitude. Selected plastic particles were analyzed for size, mass, form, and material density. This represents the first catalog of the properties of pelagic plastic debris at an ocean-basin spatial (25° latitude × 15° longitude) scale and multi-decadal temporal scale.

All samples were collected with a neuston tow, using a surface net-tow protocol that has been uniformly employed on SEA vessels for the past three decades. A neuston net (335 μm mesh and 0.5 m × 1.0 m opening) was towed along the sea surface (nominally 0.25 m of the net is submerged beneath the surface) for approximately one nautical mile at a speed of two knots and the contents of the net are strained over a 335 μm mesh sieve. All plastic particles were visually identified, hand-separated from plankton and tar, air-dried, stored in plastic bags, and archived in darkness at room temperature. Despite ever-changing scientific crews, we have found this straightforward sampling method to offer an excellent model for ongoing and future neustonic plastic studies.

The selected archived samples were weighed on an analytical balance, and the longest edge of each particle was measured with a micrometer (recorded as particle size). By appearance, we noted the plastic form, including fragments/chips, sheets (e.g., plastic bag), industrial plastic pellets, fishing/marine line, polystyrene foam, and particles undefined by the latter forms (e.g., resembled tar, or was too small for proper identification). As plastic samples represent a wide variety of materials, we used density measurements as a first-order identifier of different plastic resins (Table 1). Given that density is not a unique identifier of plastic material, we also analyzed a range of samples for carbon, hydrogen, and nitrogen (CHN) content. To evaluate this method, we analyzed recently purchased retail products and found their content consistent with CHN values calculated from the bulk chemistry of the resin monomer.

Density determination was modified from Kolb and Kolb (1991). Each sample was placed in a 40-ml glass vial with distilled water and agitated to release any air bubbles on the surface of the sample. If the sample sank, we increased the density of the solution by adding concentrated solutions of calcium or strontium chloride until the plastic piece was neutrally buoyant. If the sample floated, the density of the solution was lowered by adding ethanol until the plastic became neutrally buoyant. We then waited 15 min to assure that the samples maintained neutral buoyancy and that no air bubbles were present. One milliliter of the resulting solution was delivered via an automatic pipetter to a tared flask on an analytical balance to determine the density of the aqueous solution (g ml^{-1}). We were unable to calculate the density of polystyrene foam particles due to embedded air pockets. The precision of these measurements, as determined by triplicate analysis of numerous plastic types, was 1% or better. To test the accuracy of this approach, we collected plastic samples from recently purchased retail products labeled with plastic resin (or recycling) codes 1–6, representing different plastic types. Our density measurements of consumer plastics were consistent with published values (Table 1).

Particle sizes ranged from 0.41 to 420 mm, with more than 88% of particles less than 10 mm in length (Fig. 2). Sixty-nine percent of plastic particles measured between 2 and 6 mm. Mean particle size within each latitudinal bin ranged from 5.18 ± 1.13 (standard error) to 25.49 ± 6.45 mm and was significantly higher at 40°N (25.49 ± 6.45 mm, ANOVA, $p < 0.001$) than farther south. This is consistent with the prevalence of long line, large sheets and large fragments observed at that latitude. The majority (>95%) of plastic particles in our study had a mass less than 0.05 g and ranged from 0.0001 to 3.274 g (Fig. 2). Latitudinal mass means ranged from 0.007 ± 0.002 to 0.241 ± 0.233 g with a larger mean mass at 40°N (0.032 ± 0.016 g, ANOVA, $p < 0.001$).

The majority (99%) of plastic pieces had densities less than the mean measured density of western North Atlantic surface seawater (~1.025 g ml^{-1}), as expected. Particle-density ranged from 0.808 to 1.238 g ml^{-1} and 47% of the samples had densities between 0.97 and

Table 1
Known % carbon, hydrogen, nitrogen (CHN) content and density ranges for common consumer virgin plastic types.

Resin code	Plastic type	Acronym	C (%)	H (%)	N (%)	Known density (g ml^{-1})
5	Polypropylene	PP	85.70	14.28	0	0.85–0.92
4	Low density polyethylene	LDPE	85.70	14.28	0	0.89–0.93
2	High density polyethylene	HDPE	85.70	14.28	0	0.94–0.97
6	Polystyrene	PS	92.30	7.70	0	1.04–1.08
7	Nylon 6	PA6	63.70	9.70	12.4	1.15
3	Polyvinyl chloride	PVC	38.46	4.81	0	1.16–1.41
1	Polyethylene terephthalate	PET	62.50	4.17	0	1.38–1.41

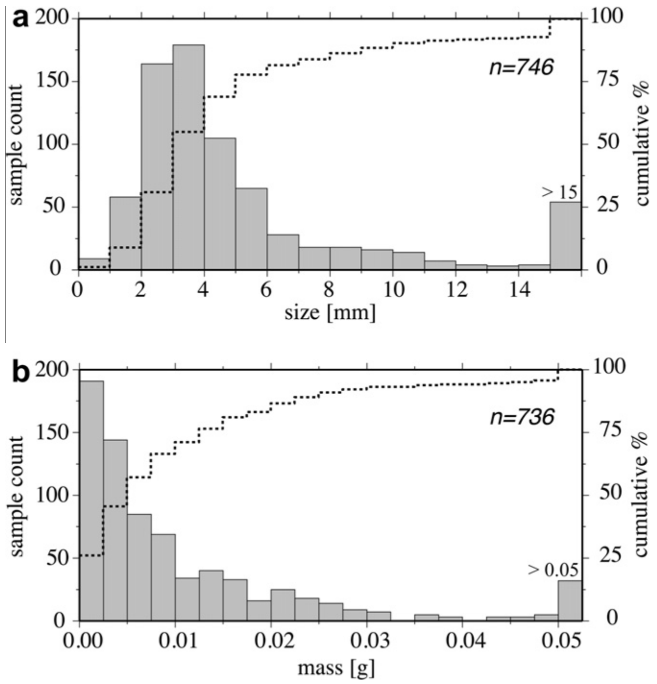

Fig. 2. Plastic sample (a) size and (b) mass histograms. Dotted lines represent cumulative percentage. The vast majority of particles were less than 10 mm in size and had a mass less than 0.05 g.

$1.04\ g\ ml^{-1}$ (Fig. 3). In comparison to the virgin resin density values listed in Table 1, sample densities between 0.97 and $1.04\ g\ ml^{-1}$ represent a range between high density polyethylene (HDPE) and polystyrene (PS), suggesting that the majority of pelagic plastics are changing as they reside at sea. Density means within each latitudinal bin ranged from 0.913 ± 0.009 (40°N) to $0.972 \pm 0.001\ g\ ml^{-1}$ (30°N). Particle densities were significantly higher at 30°N in the subtropical convergence zone ($0.972 \pm 0.001\ g\ ml^{-1}$, ANOVA, $p < 0.001$) when compared with mean sample densities enclosed in all other latitudinal bins (15°N = $0.930 \pm 0.009\ g\ ml^{-1}$, 20°N = $0.933 \pm 0.015\ g\ ml^{-1}$, 25°N = $0.950 \pm 0.004\ g\ ml^{-1}$, and 35°N = $0.957 \pm 0.002\ g\ ml^{-1}$).

To compare the density of pelagic plastic samples to plastic debris having spent less time in the open ocean, we analyzed 410 plastic pieces collected from an enclosed beach on Washburn Island, Massachusetts. Beach samples were collected weekly along a 70-m^2 transect at low tide over a 2-month period in the summer of 2009. The densities of beach plastics ranged from 0.752 to $1.39\ g\ ml^{-1}$, which, in contrast to pelagic plastic samples, more closely match the densities of common consumer plastics (Fig. 3). The high degree of overlap between the densities of beach plastic and virgin polymers, suggests that plastic resin types 1–6 are found along coastlines (consistent with Ribic et al. (2010)) and that particle densities remain largely unchanged in this environment. In contrast, processes acting at sea seems to change the density of plastic particles.

Elemental analysis of 19 plastic particles across a broad density range revealed that the plastic samples derive from three main plastic types: HDPE, low density polyethylene (LDPE), and polypropylene (PP). None of these plastic samples had an elemental composition matching other common plastics, namely polyethylene terephthalate (PET), polyvinyl chloride (PVC), solid PS, or Nylon 6 (Table 2). Two unusually dense samples (both $>1.37\ g\ ml^{-1}$) were analyzed for elemental composition and did not exhibit the CHN compositions of known plastic values (Table 1); by visual inspection they were determined to be paint chips, presumably from ship hulls. Plastic samples with densities greater than $1.025\ g\ ml^{-1}$ ($n = 6$) could theoretically be solid PS, PVC or PET that have become less dense, or a buoyant plastic that has become more dense (i.e.,

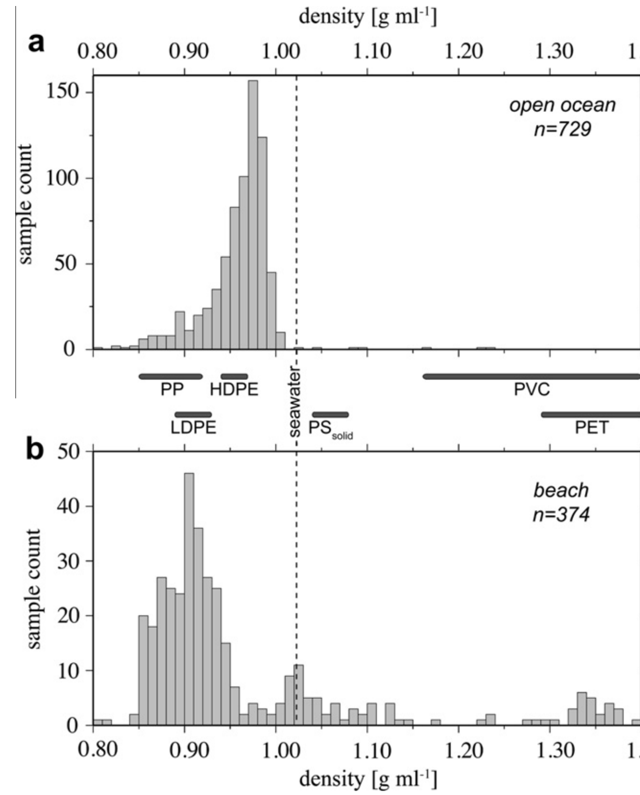

Fig. 3. Plastic density histograms of (a) open ocean and (b) beach samples, not including polystyrene foam. Horizontal bars indicate known densities of major consumer plastics. Dashed line represents measured mean western North Atlantic surface seawater density. Note that only six pelagic samples have densities greater than seawater, and that beach plastic values are consistent with the densities of common consumer plastics.

sample 19 in Table 2). However, the majority of particles have reduced % C and % H relative to their original values (85.7% C and 14.3% H), yet they exhibit variable density anomalies. Our analyses thus suggest that particle-density at sea is dynamic, and that the samples with densities between 0.97 and $1.04\ g\ ml^{-1}$ are PP, LDPE, and HDPE that have increased in density over time. In 2008, these three plastic resins composed more than 50% of total discarded plastics in US municipal solid waste (US EPA, 2009), totaling 14.5 million tons.

We propose two possible hypotheses for the density modification of pelagic plastic particles from their virgin plastic values. One is that weathering, photochemical breakdown and prolonged mechanical abrasion (Andrady et al., 1998; Corcoran et al., 2009), is preferentially altering particle-density with exposure. However, it is currently unclear if weathering can lead to increases in density, and further study is needed. More likely, another hypothesis is that biomass accumulation, often visually observed on the samples, is increasing sample densities. Our elemental analyses suggest that up to about 1% of the bulk sample content is nitrogen (Table 2). Because consumer plastics (with the exception of nylon) do not contain nitrogen, we consider nitrogen a proxy for biomass. A 1% increase in nitrogen due to biofouling would mean that approximately 7% of the total particle mass is biomass (assuming a Redfield ratio of 106:16 for the molar C:N of marine biomass, and neglecting the molar mass contribution of H):

$$1\ \text{wt.\%N}\left(\frac{\text{mol N}}{14\ \text{g N}}\right)\left(\frac{106\ \text{mol C}}{16\ \text{mol N}}\right)\left(\frac{12\ \text{g C}}{\text{mol C}}\right) = 5.7\ \text{wt.\%C}$$

$$\begin{aligned}\text{Total wt.\% biomass} &= \text{wt.\%N} + \text{wt.\%C} = 1\ \text{wt.\%} + 5.7\ \text{wt.\%}\\ &= 6.7\ \text{wt.\% biomass}\end{aligned}$$

Table 2
Elemental analysis (% CHN content) of plastic samples across a broad density range. Note: % C and % H consistency with virgin PP, LDPE, and HDPE values in Table 1, and that % N > 0 in all samples.

Sample #	Density (g ml^{-1})	C (%)	H (%)	N (%)	Notes
1	0.859	84.82	13.51	0.47	Brown, transparent fragment
2	0.889	85.09	14.53	0.42	White, translucent fragment
3	0.892	83.36	13.39	0.63	Gold, weathered pellet
4	0.896	84.87	13.86	0.05	Mint-colored line
5	0.906	84.52	13.96	0.40	Off-white translucent line
6	0.921	83.41	13.74	0.54	Off-white fragment
7	0.923	85.79	13.77	0.41	Black pellet-like fragment
8	0.940	82.85	13.53	0.82	Blue, irregular fragment
9	0.942	84.63	13.69	0.59	Black fragment
10	0.957	84.36	13.61	0.03	White line
11	0.960	85.33	14.15	0.52	White, large, translucent chip
12	0.960	84.34	13.96	0.45	Off-white fragment
13	0.960	84.16	13.74	1.07	Blue fragment
14	0.980	83.56	13.83	0.62	Off-white fragment
15	0.980	79.13	13.10	0.79	Yellowed, rough fragment
16	0.980	82.55	13.75	0.41	Off-white fragment
17	0.996	83.48	13.81	0.61	Off-white fragment
18	0.998	81.62	13.46	0.45	Off-white fragment
19	1.042	83.27	13.81	0.60	White, opaque fragment

Assuming a density of dry microbial biomass to be 1.5 g ml^{-1} (Bratbak and Dundas, 1984), a mass-balance calculation indicates that a plastic particle with an initial density of 0.91 g ml^{-1} (corresponding to PP or LDPE, and the modal value observed in the beach sample set) would increase in density to 0.950 g ml^{-1} with an amount of biofouling constrained by the measured 1% gain in nitrogen:

$$0.91\ \text{g ml}^{-1}(93.3\%\ \text{plastic}) + 1.5\ \text{g ml}^{-1}(6.7\%\ \text{biomass}) = 0.950\ \text{g ml}^{-1}$$

This estimate of density increase is comparable to the 0.960 g ml^{-1} mean density value for pelagic plastic particles.

The nature of plastic debris changed between our two study periods, 1991–1995 and 2004–2007 (Table 3). In the 1990s mean particle size was 10.66 ± 1.60 mm compared to 5.05 ± 0.35 mm in the 2000s (ANOVA, $p < 0.001$), although the shapes of the size histograms from each time period are quite similar. Sixteen percent of plastic particles were 10 mm and larger in the 1990s, compared with the more recent study period when only 6% were 10 mm and larger. This could indicate that plastic particles are decreasing in size on the ocean surface, possibly due to the amplifying effects of mechanical abrasion and photochemical breakdown on particles with long residence times in the ocean. Mean particle-density increased slightly but significantly from the 1990s to 2000s by 0.010 g ml^{-1} (from 0.955 ± 0.002 to 0.965 ± 0.002 g ml^{-1}, ANOVA, $p < 0.001$). Fragments, or broken pieces of larger objects, composed the majority of plastic particles at all latitudes in both decades (Fig. 4). In addition, we found fewer pellets and sheets in the 2000s – only five pellets compared to 47 in the 1990s, and four sheets compared to 19 in the 1990s. Proportionate to those reductions, there were 18% more fragments in the North Atlantic in the 2000s, suggesting a decadal shift in plastic particle form.

Density measurements can be a powerful aid in characterizing the plastic types present in the ocean. They also demonstrate that chemical and physical particle properties change at sea, likely due to microbial biofouling. Differences in density distributions of beach and pelagic plastic debris provide critical data for understanding debris sources, transport, and fate; the utility of these data emphasize the need for future studies to address the factors that change plastic densities in differing marine environments.

Our CHN analyses suggest that plastic particles are increasing in density during their residence in the open ocean. Analyzing samples for CHN content uniquely determines plastic type and simultaneously offers an indication of biofouling. However, CHN analysis is destructive, as it requires sample combustion, and does not yield as much information as mid-infrared spectrophotometric analysis. An alternative, nondestructive method for determining polymer type is attenuated total reflection Fourier-transform infrared spectroscopy (FT-IR ATR) (Corcoran et al., 2009; Browne et al., 2010), but this technology is relatively scarce and thus commercial analyses are prohibitively expensive. In contrast, density measurements are inexpensive, can be made with a minimal capital investment, and when combined with CHN analyses offer a powerful method to determine how plastic particles persist and transform in the marine environment.

Cataloging basic properties of individual plastic debris also addresses broader ecological questions. For example, our observed decadal shift in particle form is comparable to recent studies on seabird plastic ingestion, which suggest that there has been a shift over the last two decades in the type, but not quantity, of consumed pelagic plastic debris (Vlietstra and Parga, 2002; Ryan,

Table 3
Mean and standard error for the size, mass, and density of plastics by latitude between 1991–1995 and 2004–2007.

Latitude (°)	Size (mm)		Mass (g)		Density (g ml^{-1})	
	1990s n = 392	2000s n = 354	1990s n = 396	2000s n = 350	1990s n = 381	2000s n = 348
40	30.64 ± 8.86	13.04 ± 3.75	0.017 ± 0.006	0.068 ± 0.054	0.909 ± 0.011	0.922 ± 0.016
35	9.72 ± 2.23	3.83 ± 0.48	0.012 ± 0.001	0.008 ± 0.004	0.957 ± 0.002	0.955 ± 0.014
30	5.98 ± 0.46	5.17 ± 0.42	0.025 ± 0.005	0.012 ± 0.002	0.967 ± 0.004	0.974 ± 0.002
25	8.01 ± 2.67	3.33 ± 0.55	0.012 ± 0.004	0.004 ± 0.001	0.958 ± 0.008	0.945 ± 0.005
20	6.23 ± 2.47	2.74 ± 0.71	0.012 ± 0.003	0.003 ± 0.001	0.941 ± 0.016	0.904 ± 0.041
15	4.76 ± 1.63	4.15 ± 0.97	0.005 ± 0.004	0.010 ± 0.050	0.944 ± 0.007	0.911 ± 0.015

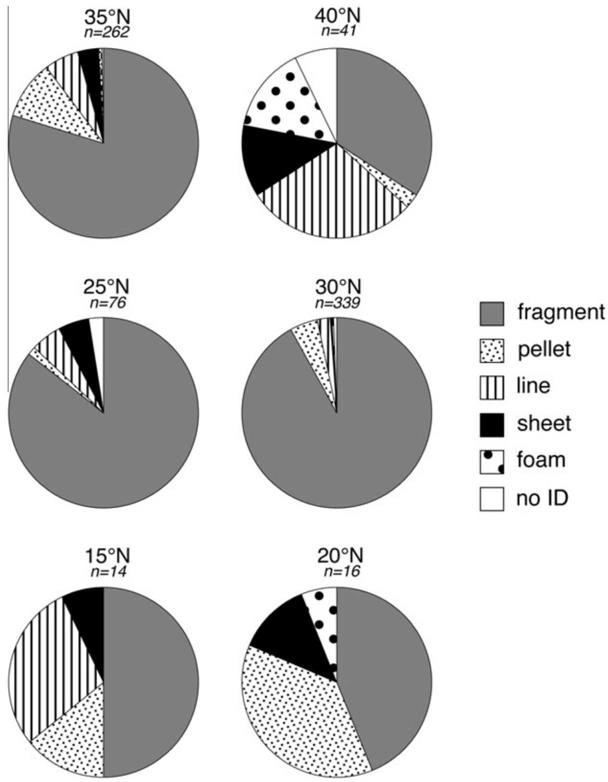

Fig. 4. Proportion of six principal plastic forms at every 5th parallel. Note that industrial resin pellets made up a high percentage (38%) of particles at 20°N. Marine-related line composed a sizeable portion (29%) of particle forms at 15°N and 40°N, latitudes at which the fishing industry is more active. Form characterization (Shaw and Day, 1994; Vlietstra and Parga, 2002) offers a valuable tool for geographic and temporal comparison.

2008; Ryan et al., 2009). Particle-density data are critical for understanding what types of plastics are floating (or sinking) and are potential food for surface-feeding organisms. The smaller size and mass range of plastic particles described in this study have yet to be evaluated within the context of both species and ecological consequences. Establishing the size, mass, and composition of plastics that persist in the surface ocean is important to understand the impacts of plastics on seabirds and to identify and mitigate the sources of this debris.

Determining the range and statistical distribution of individual-particle size and mass is not only helpful in understanding the transport of invasive species, but is also useful in considering what potential organisms may ingest the debris and how the particle may absorb organic pollutants. There are ecological consequences of having larger plastic particles in certain regions; Minchin (1996) demonstrated that some species, such as *Lepadid cirripedes*, prefer larger substrata for settlement and transport across the ocean, as approximately six barnacles can fit on each substrate. Plastics such as foam packing pellets, flat plastic fragments, and line accounted for 25% of all substrata used by those barnacles (Minchin, 1996). Understanding the range and distribution of particle form is beneficial when considering how various animal predators may be attracted to different shapes, how particle form offers varying surface area potential to absorb anthropogenic chemicals, and how form may be helpful in indicating debris sources and later targeting management. These data also give us a range to gauge the ability of different nets and mesh sizes to accurately sample plastic debris. We intend for this data to provide a baseline for future studies examining plastic debris in the open ocean, with hopes that it will allow for comparison and monitoring of both pelagic and coastal areas.

As international plastic production continues to increase, it is crucial not only to understand marine geographic distributions and quantities of plastic, but also to consider the specific properties of plastic particles themselves. This study establishes a robust baseline for the size, mass, and composition of individual plastic marine debris particles in the western North Atlantic. The large spatial and temporal scales of this study offer compelling and unique insights into particle persistence and fate, potential debris sources, and some of the broader consequences of plastic debris on marine ecosystems.

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References

Andrady, A.L., 2003. Plastics and The Environment. John Wiley and Sons, West Sussex, England.
Andrady, A.L., Hamid, S.H., Hu, X., Torikai, A., 1998. Effects of increased solar ultraviolet radiation on materials. J. Photochem. Photobiol. B 46, 96–103.
Azzarello, M.Y., Van Vleet, E.S., 1987. Marine birds and plastic pollution. Mar. Ecol. Prog. Ser. 37, 230–295.
Barnes, D.K.A., 2002. Invasions by marine life on plastic debris. Nature 416, 808–809.
Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B 364, 1985–1998.
Bratbak, G., Dundas, I., 1984. Bacterial dry-matter content and biomass estimations. Appl. Environ. Microbiol. 48, 755–757.
Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *M. edulis* (L.). Environ. Sci. Technol. 42, 5026–5031.
Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol.. doi:10.1021/es903784e.
Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters. Science 178, 749–750.
Colabuono, F.I., Taniguchi, S., Montone, R.C., 2010. Polychlorinated biphenyls and organochlorine pesticides in plastics ingested by seabirds. Mar. Pollut. Bull. 60, 630–634.
Colton, J.B., Knapp, F.D., Burns, B.R., 1974. Plastic particles in surface waters of the northwestern Atlantic. Science 185, 491–497.
Corcoran, P.L., Biesinger, M.C., Grifi, M., 2009. Plastics and beaches: a degrading relationship. Mar. Pollut. Bull. 58, 80–84.
Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.
Giam, C.S., Chan, H.S., Neff, G.S., Atlas, E.L., 1978. Phthalate ester plasticizers: a new class of marine pollutant. Science 199, 419–420.
Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings, entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. B 364, 2013–2025.
International Pacific Research Center, 2008. Tracking ocean debris. IPRC Climate, 8, 14–16. Available from: <http://iprc.soest.hawaii.edu/newsletters/iprc_climate_vol8_no2.pdf>.
Kolb, K.E., Kolb, D.K., 1991. Method for separating or identifying plastics. J. Chem. Educ. 68, 348.
Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Pollut. Bull. 18 (6B), 319–326.
Law, K.L., Morét-Ferguson, S., Reddy, C.M., Peacock, E.E., Maximenko, N.A., 2010. A 22-year record of plastic marine debris in the Atlantic Ocean. Eos Trans. AGU 91 (26). Ocean Sci. Meet. Suppl., Abstract # IT31C-02.
Li, X., Zeng, Z., Chen, Y., Xu, Y., 2004. Determination of phthalate acid esters plasticizers in plastic by ultrasonic solvent extraction combined with solid-phase microextraction using calix [4] arene fiber. Talanta 63, 1013–1019.
Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. 35, 318–324.
Minchin, D., 1996. Tar pellets and plastics as attachment surfaces for *Lepadid cirripedes* in the North Atlantic Ocean. Mar. Pollut. Bull. 32 (12), 855–859.
Pichel, W.G., Churnside, J., Veenstra, T., Foley, D., Friedman, K., Brainard, R., Nicoll, J., Zheng, Q., Clemente-Colón, P., 2007. Marine debris collects within the North Pacific subtropical convergence zone. Mar. Pollut. Bull. 54, 1207–1211.
Pruter, A.T., 1987. Sources, quantities and distribution of persistent plastics in the marine environment. Mar. Pollut. Bull. 18 (6B), 305–310.

Ribic, C.A., Sheavly, S.B., Rugg, D.J., Erdmann, E.S., 2010. Trends and drivers of marine debris on the Atlantic coast of the United States 1997–2007. Mar. Pollut. Bull.. doi:10.1016/jmarpolbul.2010.03.021.

Ryan, P.G., 2008. Seabirds indicate changes in the composition of plastic litter in the Atlantic and south-western Indian Oceans. Mar. Pollut. Bull. 56 (8), 1406–1409.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. Trans. R. Soc. B 364, 1985–1998.

Shaw, D.G., Day, R.H., 1994. Colour- and form-dependent loss of plastic micro-debris from the North Pacific Ocean. Mar. Pollut. Bull. 28, 39–43.

Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41, 7759–7764.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philos. Trans. R. Soc. B 364, 2027–2045.

Thompson, R.C., Olsen, Y., Mitchell, R., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.

US EPA, 2009. Municipal Solid Waste in the United States: 2008 Facts and Figures. United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC (EPA530-F-009-021).

Van Dolah, R.F., Burrell, V.G., West, S., 1980. The distribution of pelagic tars and plastics in the South Atlantic Bight. Mar. Pollut. Bull. 11, 352–356.

Vlietstra, L.S., Parga, J.A., 2002. Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering Sea. Mar. Pollut. Bull. 44, 945–955.